Multi-Criteria GIS Analysis and Geo-Visualisation of the Overlap of Oil Impacts and Ecosystem Services in the Western Amazon

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Abstract

Oil extraction operations can be found in all types of environment, including the most threatened and delicate tropical rainforests. The Western Amazon has been widely recognised for its biodiversity and important ecosystem services, but it is also rich in oil reserves. The governments of Colombia, Ecuador and Peru have been increasingly developing and exploiting oil resources in these remote areas and this exploitation is an important contribution to their national economies. This analysis aims to inform a more sustainable development of extractives in the region using innovative techniques of geo-visualisation. The results yield a comprehensive oil impact assessment for the region and then highlight environmentally important zones to finally visualise areas of significant environmental risk based on future planned oil developments. The maps show that areas most affected by oil activities, such as the Yasuni National Park, in Ecuador and the Corrientes River Basin, in Peru are also the source of ecosystem services and furthermore areas as the Manu National Park, in Peru, are in risk of losing their ecosystem services value due to oil development expected in the near future. A better understanding of the situation supported by scientific information and innovative geo-visualisation will help to put in place and enforce policies and thus minimise the socio-environmental impacts of the activity while maintaining the production of oil and associated revenue that is vital for the region's economy.

1. Introduction

Oil exploration in Ecuador, Peru and Colombia started in the early 1900s in the Gulf of Guayaquil Ecuador, the area of Talara in the northern coast of Peru and the Magdalena River Basin in Colombia (Hanratty, 1991 and Hudson, 1992). The oil industry is capable of generating significant revenues especially at times of high demand but it equally needs considerable investment, especially when working in isolated and remote areas (Ramos and Veiga, 2011). The infrastructure and activities required for oil exploitation traditionally include roads, wells, pipeline installations and construction of large production facilities (Baynard, 2011). The impacts of all these infrastructures are of great concern when they are built in delicate and important areas for conservation and the provision of ecosystem services. The national oil company in Colombia, Ecopetrol is in control of a large pipeline system that covers a significant part of the centre and north of the country and in minor extent in the southern border (Ecopetrol, 2010). In Ecuador, the Trans Ecuadorian Pipeline, SOTE and the OCP and Heavy Oil Pipeline are the main oil infrastructures that carry oil across the Andes (Mirabik, 1991 and Lucero, 1997). The oil and gas industries in Peru have constructed two major pipelines to extract resources from the Amazon all the way to the Pacific Coast for export and internal supply (Perupetro, 2010). There are several development projects, some already underway, that aim to expand the extraction of resources particularly towards less-explored areas in the Amazon (Presidency of Ecuador, 2012). On the other hand, the Western Amazon has been widely recognised for its high species richness and endemism. In fact, 20% of the Western Amazon territories are under some type of protection due to the encompassed biodiversity. Even more, there are more than a thousand indigenous territories (Bass et al., 2010, RAISG, 2009, Finer et al., 2008 and Lucero, 1997). One of the major impacts of oil contamination is on water resources. It is estimated as part of the Texaco lawsuit in Ecuador that it would cost some USD 27 billion to clean-up the polluted groundwater in the affected region (Amazon Watch, 2009). Furthermore, local people in the whole Western Amazon depend on sources of clean water that come from riverbeds and groundwater sources, as well as rainfall water collection particularly in the areas where oil pollution has been significant (UNICEF, 2009). The provision of ecosystem services has been recognised as a priority in the oil-impacted areas (Ojeda et al., 2008 and Bastian et al., in press) thus scientific information would help to better maintain their supply. The aim of this study is to provide information for a more sustainable development of extractives in the Western Amazon by highlighting the ecosystem service impacts of oil developments and using innovative GIS techniques to visualise and understand the risks and propose an optimal extraction and distribution strategies with lower socio-environmental impacts. To achieve this aim, firstly the construction of a comprehensive geographic database with all variables involved was set as an objective. On a second stage, the development of new techniques of geo-visualisation is set as a target in order to better represent and analyse focus areas.

2. Methods

The Western Amazon comprises areas of Colombia, Ecuador, Peru, Bolivia, Venezuela and Brazil. Geographically, our study area lies within the coordinates of latitude 10°N to 20°S, and 80°W to 60°W of longitude. Even though the GIS was developed and applied over the whole area, the focus of the analysis is on the Amazon of Colombia, Ecuador and Peru, due to similarities in both the ecosystem services and history of oil industry in these countries (Finer et al., 2008). An extensive research on publicly available data was completed. Data from official and governmental sources were combined with publicly available data from private (i.e. oil companies) and civil (i.e. NGOs) sectors, in order to build a comprehensive geographic database. The collected datasets include data for oil blocks, pipelines, wells, waste pits, stations, flares, as well as roads, local communities and river networks. Additional information on environmental variables (elevation, water balance, land cover, local drainage direction and watersheds) as well as social variables (administrative boundaries, urban areas, land use) was derived and merged from the SimTerra database (Mulligan, 2010a). Data research and gathering was exhaustive to assure that all the used variables cover the entire focus area. The pioneering way to compile all the available information into a consistent geographic database was achieved by keeping a simple raster format, obtained with the Inverse Distance Weighing deterministic method for multivariate interpolation (ESRI, 2011) maintaining a constant resolution, and built-in rules with the purpose of ease of update when additional data are included. Only when data was available for the whole focus area was it included in the analysis to maintain consistency in the weighting and results. More detailed information on the datasets included in the analysis is presented in Table 1.

Table 1: List of variables used for the GIS multi-criteria analysis of the oil activities impacts and ecosystems services provision in the Western Amazon

variable	**source of information**	**data type**	**Units**
Oil pipelines	(PETROECUADOR, 2010, ECOPETROL, 2010, PERUPETRO, 2010, EquitableOrigin, 2011and UNIGIS, 2010)	polyline	Km
Oil wells*	(UNIGIS, 2010 and ANH, 2012)	point	
Block - concessions	(Jenkins, 2009, ANH, 2012 and IBC, 2009)	polygon	Km^2
Elevation	(Farr and Kobrick, 2000)	raster	m(a.s.l)
Roads	(FAO-GIEWS, 2008)	raster	pixels
Urban areas	(CIESIN et al., 2004)	raster	classes
Amphibians spp. Richness	(Mulligan, 2010a using (IUCN et al., 2008b)	raster	# spp.
Birds spp. richness	(Mulligan, 2010a)	raster	# spp.
Mammals spp. Richness	(Mulligan, 2010a using (IUCN et al., 2008a)	raster	# spp.
Reptiles spp. Richness	(Mulligan, 2010a using (IUCN, 2010)	raster	# spp.
Protected Areas	(UNEP-WCMC, 2009)	raster	unique ID
Tree coverage	(Hansen et al., 2006)	raster	fraction
Carbon Stock	(Ruesch and Gibbs, 2008)	raster	$tonnes/Km^2$
Local water balance	(Hijmans et al., 2005 and Mulligan and Rubiano, 2010)	raster	mm/year

* in Colombia the mapped wells are currently not in exploitation within the area of study

Thus all data were pre-processed and when necessary rasterised to match a common resolution of 1 km per pixel. ArcGIS (v.10.0; ESRI, 2011), PCRaster (v.Nov.2009 and Utrecht University, 2009) and R (v.2.15.2; R, 2008) software packages were used for data management, geo-visualisation and analysis. Due to the large range of factors that determine the impact of oil activities in terrestrial environments, the most effective method to analyse variables of diverse units is a multi-criteria analysis (Boroushaki and Malczewski, 2010). First, a comprehensive analysis of the current oil infrastructure was performed with all the relevant variables to determine the extent of the oil impact in an index. Second, biological and physical variables were combined to determine an ecosystem services index by examination of the potential (i.e. provided but not necessarily used) ecosystem services (Mulligan et al., 2010). These services are calculated locally for every cell of analysis. Finally, the resulting oil impact and ecosystem services indices are brought together within a bivariate geo-visualisation in order to identify areas of high and low risk of significant ecosystem service loss. For the oil impact index it is stated that the main impacts are on-site infrastructure (Baynard, 2011and Goosem, 2004) thus they were given a higher weight of impact. However, off-site effects can also be of noticeable impact hence an influence area of the infrastructure is assigned to the neighbouring pixels for this index. Major oil infrastructures (i.e. pipelines and oil wells) are assumed to be the main causes of impact of the oil industry and occur on point sites. Roads built and maintained by the oil activities are the drivers of urban development and deforestation hence also included and properly weighed as described below. In terms of the ecosystem services index there were several assumptions and considerations to make. All biodiversity variables were included as number of threatened species due to the intrinsic value of biological diversity within an ecosystem (Eichner and Pethig, 2009). Secondly protected areas are included as Boolean maps since they are, by definition, environmentally important zones where the human impact is null or at least controlled to be at its minimum. Third, tree coverage (as a percentage) and carbon stock (in tonnes/Km^2) help to identify the areas where deforestation processes have not taken place and carbon storage services are of great potential value. Finally, water services are assumed to be locally represented by water balance data (in mm/year), which was calculated using the FIESTA hydrological model (Mulligan and Burke, 2005), resulting in the water available for use at the surface. The weighting of criteria for the analysis was done by adopting the ratio estimation method (Malczewski, 2004). Initially all variables for oil impact (oil pipelines, oil wells, oil concessions, roads and urban areas) were ranked from 1 to *n* in order of their relative weight or impact (i.e. in relation with the other considered variables), assigning 1 to the variable of highest impact and *n* to the lowest. The ecosystem services variables (threatened species of amphibians, birds, mammals and reptiles, protected areas, tree coverage, carbon stock, and water balance) were ranked in the same way in a second group of criteria. Then, for each criterion within both groups a fractional value fr is assigned according to the absolute impact of the variable within the pixel ($1<fr< 100$). In the next step, a ratio r is derived by dividing every fractional value by the maximum fraction value amongst the group (Equation 1)

$$r_i = \frac{fr_i}{\max fr_{i-n}}$$

Equation 1

Where fr_i is the fraction of a variable i and max. fr_i corresponds to the maximum value within the range of the variable. From this point an initial weight value is calculated by dividing each ratio by the rank score (Equation 2).

$$w_i = \frac{r_i}{\mathrm{rank}_i}$$

Equation 2

Where w_i is the weight for a variable, r_i is its ratio and rank_i corresponds to the assigned rank for the variable. Finally, a normalised weight ($0.00<w_Z<1.00$) is calculated for each criterion dividing it by the sum of weights (Equation 3).

$$w_Z = \frac{r_i}{\sum w_i}$$

Equation 3

Where w_Z is the final normalised weight for a variable i. For the oil impact index interpolation an additional measure was included aiming to show the influence that a particular feature (e.g. oil pipelines, oil wells) has within or around the pixel that it occupies. In the ecosystem services equivalent variables were given equal rank and then weighed using the described method (Table 2). The spatial neighbourhood of influence used for the oil impact index (Table 2, last column) is independent from the weighing process and was assigned according to expert advice (Larrea, M. *pers. comm.*). The influenceis defined by the circular neighbourhood of ratio equal to the number of influencing pixels and in the case of oil wells multiplied by the total of individual wells found within that pixel. Using the normalised weights a raster map was derived by interpolation for every variable. Then they were all added into a resultant map that represents each index from 0 (lowest) to 1 (highest). In a final stage a script brings together both indices, oil impact and ecosystem services and allows theirgeo-visualisation in a bivariate map. For this, each dataset was divided in ten data bins using as break points the Jenks Optimisation Method (ESRI, 2011) and excluding the values of zero since they skewed the histogram and data breaks and allowing to represent the clusters of classes within both datasets. Using the bin information, achoropleth colour scale was derived using the RGB colour model, where two variables can be represented within a bi-dimensional space (after Holland, R. *unpublished code*). Then, the spatial information of every cell is added to the code in order to represent them within the appropriate geographic coordinates. The automatized script delivers a final bivariate map, which represents the risk of significant ecosystem services loss.

3. Results

A total of 1678 oil wells were mapped in the Western Amazon including Ecuador (59%), Peru (38%) and in very minor extent in Colombia (3%). The major pipelines in the studied countries cover an extension of 11,185 Km, since they all cross mainly from East to West across the Andes towards the Pacific Coast. From this total of major pipelines 30% lies over the Western Amazon crossing major rivers along their way. Additionally, a considerable network of secondary distribution pipelines of smaller diameter is known to be present in the area, although they were not included in this study. The road network in the Western Amazon totals 30,483 Km mainly secondary roads which are a major cause of habitat fragmentation. The oil blocks in the Western Amazon cover an area of 657,000 Km^2 and this corresponds to 74% of the Peruvian Amazon 65% of the Ecuadorian Amazon and only 4% of the Colombian portion of the Amazon. The resulting oil impact index (Figure 1) shows major impacts on the Ecuadorian Amazon particularly in the northern areas, which validates the index since most of the oil development has taken place in these zones during the last 44 years.

Table 2: List of variables and weight calculation for the analysis of the oil impacts and ecosystem services in the Western Amazon

Oil Impact	**Rank**	**Fraction**	**Ratio**	**Weight**	**Normalised weight**	**Influence (pixel)**
Oil pipelines	2	100	1	2	0.27	2
Oil wells	1	100	1	4	0.54	3*x**
Block - concessions	3	50	0.5	0.67	0.09	1
Roads	4	50	0.5	0.5	0.07	2
Urban areas	5	25	0.25	0.2	0.03	1
			Total	7.37	1	
Ecosystem Services						
Threatened spp. amphibians	3	10	0.1	0.03	0.02	
Threatened spp. birds	3	10	0.1	0.03	0.02	
Threatened spp. mammals	3	10	0.1	0.03	0.02	
Threatened spp. reptiles	3	10	0.1	0.03	0.02	
Protected Areas	3	10	0.1	0.03	0.02	
Tree coverage	2	35	0.35	0.18	0.12	
Carbon Stock	2	35	0.35	0.18	0.12	
Water Balance	1	100	1	1	0.66	
			Total	1.52	1	

* The influence within the pixel was multiplied by the number (x) of wells mapped within the cell

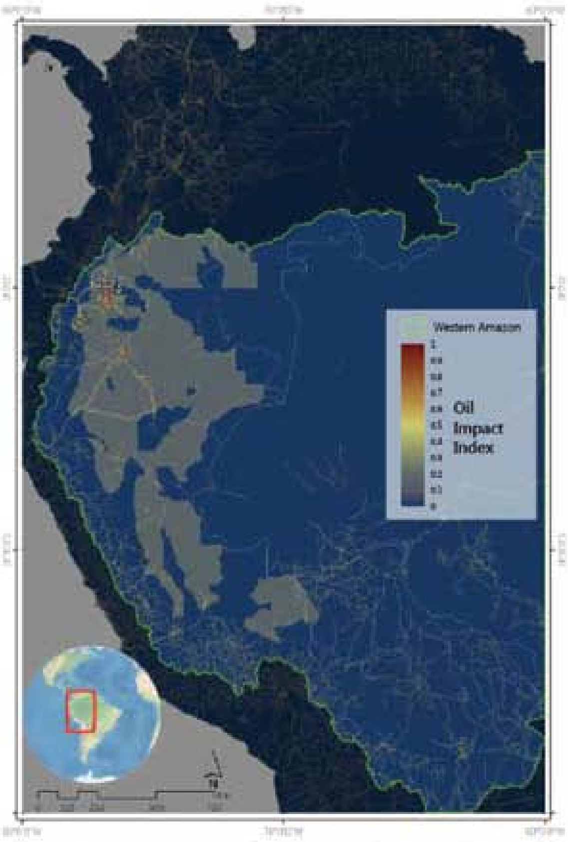

Figure 1: Oil impact index (0-1) for the Western Amazon, at 1 Km resolution

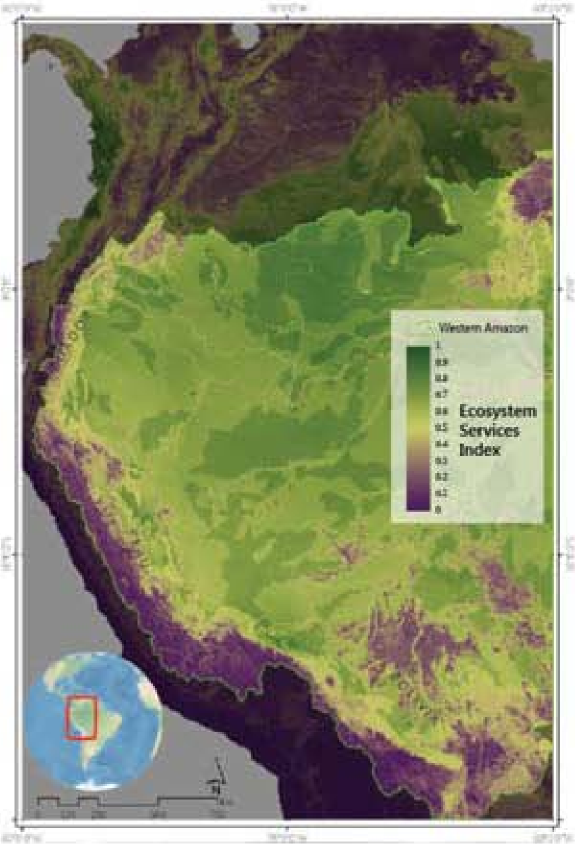

Figure 2: Ecosystem services index (0-1) for the Western Amazon, at 1 Km resolution

The impact is equally high on the Corrientes River area in Peru, where there has been oil extraction for the past four decades. In the Colombian Amazon, the impacts are less significant due to the lower oil development in the area which is used as a control area. High values are also observed along the path of the major pipelines. Statistically, the data distribution shows that up to the third quantile values are close to 0 (mean=0.03), and the top 10% of the values (max=0.91) are due to high on-site localised impacts. Focusing on the resulting maps of ecosystem services index, high numbers of species are concentrated across the whole Western Amazon. Particularly, the highest values for threatened amphibians (up to 133 spp./Km^2) are found in the Yasuni area in Ecuador and the conservation area of Imiria in Peru. Bird species numbers show even higher values in the lower Eastern Andes of Ecuador (735 spp./Km^2) and the Pacaya-Samiria area in north-eastern Peru. For threatened mammals, there is high concentration in the Manu National Park in south-eastern Peru (200 spp./Km^2) and across the lower Andes all the way up to the Amazonas Department in southern Colombia. These values are consistent with the literature (Bass et al., 2010). The protected areas account for a total of 2.3×10^6 Km^2 which represent 26% of the total area of study although the bigger areas are actually located on the extensive Amazon portion of Brazil. Analysing the ecosystem services map (Figure 2), the whole Western Amazon holds great importance with high values (above 0.5) particularly within protected areas due to their high levels of carbon storage and commonly positive water balance, assumed to be the source of good quality drinking water. When looking at the levels of importance in Ecuador the Yasuni National Park and small portion of the Cuyabeno Reserve in the north are of high importance. Equally importance is assigned to the areas of Pacaya-Samiria National Reserve as well as Manu National Park in Peru. Statistically, the data show a bimodal distribution with a third quantile of 0.44 and a maximum value of 0.75 in areas where all ecosystem services are high. When combining both indices and geo-visualising them in a bivariate map, the areas of north-eastern Ecuador and northern Peru show higher levels in both oil impact and ecosystem services indices. This fact was not considered when the oil facilities and infrastructure were located in the middle of the rainforest areas which have been recognised to contain high biodiversity levels (Bass et al., 2010) and proven to be the source of ecosystem services (Ojeda et al., 2008, Eichner and Pethig, 2009 and Mulligan, 2010a). Furthermore, it is important to look at the areas with high levels of ecosystem services (above the third quantile) and in the medium range of the oil impact index which are areas that have not been "oil developed" but are included in plans of future developments. These areas clearly have a high risk of ecosystem service loss and in general they coincide with protected areas and indigenous territories that overlap with oil concessions.

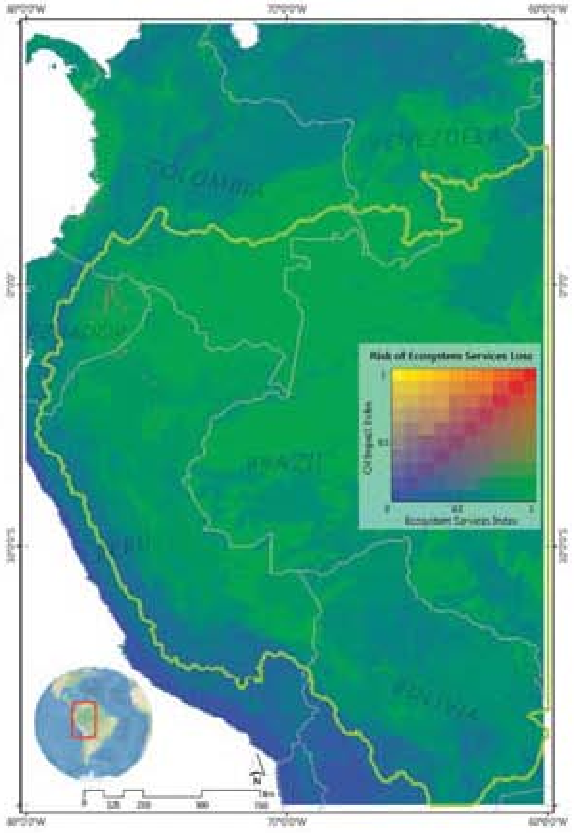

Figure 3: Risk of ecosystem services loss (0-1) obtained combining in a bivariate space both oil impact and ecosystem services indices, for the Western Amazon, at 1 Km resolution

4. Discussion and Conclusion

A comprehensive GIS analysis of oil infrastructure potential for impact and environmental importance has not been performed in such detail for the whole of the Western Amazon. Finer et al., (2009) successfully described the oil situation by mapping the oil concessions but further and more detailed work was needed to evaluate the actual extent of the impact. Furthermore, identifying areas of risk of ecosystem service loss due to oil activities is a step forward towards a cleaner and more environmentally sound extraction of resources. Applying new techniques of geo-visualisation proved to be an innovative approach to bring variety scientific information within a single map. The resulting maps were discussed with experts from both the environmental and industry fields, and there is a general agreement, and hence validation, on the extent of impact and the importance of the potential ecosystem services that the areas hold. As a regional study the information produced can help to better understand the current trans-national situation of oil in the region beyond the official reports from the environmental agencies in each country. Additionally, the reliability of the indices is supported by objective and independent scientific data. Consequently, the results can effectively be of use and application on informed decision and policy making. Open and public information may be of use and support to all stakeholders, from oil companies, local governments, civil organisations through to indigenous communities living and depending on the land, its resources and its ecosystem services. Currently, Ecuador and Peru are signing agreements to extend the oil frontier across their borders by integrating the North-Peruvian pipeline with the oil concessions to be exploited in South-eastern Ecuador (Presidency of Ecuador, 2012). For these reasons, the need for independent sources of scientific information is greater. This study contributes to that need by bringing scientific information within a spatial context and making it available, through innovative technology, in an understandable and approachable way.

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